

Neutral weak current two-body contributions in inclusive scattering from ^{12}C

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An *ab initio* calculation of the sum rules of the neutral weak response functions in ^{12}C is reported, based on a realistic Hamiltonian, including two- and three-nucleon potentials, and on realistic currents, consisting of one- and two-body terms. We find that the sum rules of the response functions associated with the longitudinal and transverse components of the (space-like) neutral current are largest and that a significant portion ($\simeq 30\%$) of the calculated strength is due to two-body terms. This fact may have implications for the MiniBooNE and other neutrino quasi-elastic scattering data on nuclei.

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In recent years, there has been a surge of interest in inclusive neutrino scattering off nuclear targets, mostly driven by the anomaly observed in the MiniBooNE quasi-elastic charge-changing scattering data on ^{12}C [1], i.e., the excess, at relatively low energy, of measured cross section relative to theoretical calculations. Analyses based on these calculations have led to speculations that our present understanding of the nuclear response to charge-changing weak probes may be incomplete [2], and, in particular, that the momentum-transfer dependence of the axial form factor of the nucleon may be rather different from that obtained from analyses of pion electroproduction data [3] and measurements of neutrino and anti-neutrino reactions on protons and deuterons [4–7].

The accurate calculation of the weak inclusive response of a nucleus like ^{12}C is a challenging quantum many-body problem. Its difficulty is compounded by the fact that the energy of the incoming neutrinos is not known (in contrast, for example, to inclusive (e, e') scattering where the initial and final electron energies are precisely known). The observed cross section for a given energy and angle of the final lepton results from a folding with the energy distribution of the incoming neutrino flux and, consequently, may include contributions from energy- and momentum-transfer regions of the nuclear response where different mechanisms are at play: the threshold region, where the structure of the low-lying energy spectrum and collective effects are important; the quasi-elastic region, which is (naively, see below) expected to be dominated by scattering off individual nucleons; and the Δ resonance region, where one or more pions are produced in the final state.

In recent years, a number of studies have attempted to provide a description of the nuclear weak response in this wide range of energy and momentum transfers. They typically rely on a relativistic Fermi gas [8, 9] or relativistic mean field [10, 11] picture of the nucleus. Some, notably those of Ref. [12, 13], include correlation effects in the random-phase approximation induced by

effective particle-hole interactions in the N - N , Δ - N , N - Δ and Δ - Δ sectors, use various inputs from pion-nucleus phenomenology, and lead to predictions for electromagnetic and strong spin-isospin response functions of nuclei, as measured, respectively, in inclusive (e, e') scattering and in pion and charge-exchange reactions, in reasonable agreement with data.

In the present manuscript, we report on a study of the neutral weak response of ^{12}C , based on a dynamical framework in which nucleons interact among themselves with two- and three-body forces and with external electroweak probes via one- and two-body currents—elsewhere [14], we have referred to this framework as the standard nuclear physics approach (SNPA). While SNPA allows for an *ab initio* treatment of the nuclear response in the threshold and quasi-elastic regions and, as such, constitutes a significant improvement over the far more phenomenological approaches mentioned above, it has nevertheless severe limitations: it cannot describe—at least, in its present formulation—the Δ -excitation peak region, since no mechanisms for (real) single- and multi-pion production are included in it. However, the above proviso notwithstanding, the sum rules of weak neutral response functions, which we consider here, should provide useful insights into the nature of the strength seen in the quasi-elastic region and, in particular, into the role of two-body terms in the electroweak current.

The differential cross section for neutrino (ν) and antineutrino ($\bar{\nu}$) inclusive scattering off a nucleus—the processes $A(\nu_l, \nu'_l)$ and $A(\bar{\nu}_l, \bar{\nu}'_l)$ induced by the neutral weak current (NC)—can be expressed in terms of five response functions as follows [15]

$$\left(\frac{d\sigma}{d\epsilon' d\Omega} \right)_{\nu/\bar{\nu}} = \frac{G_F^2}{2\pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[R_{00} + \frac{\omega^2}{q^2} R_{zz} - \frac{\omega}{q} R_{0z} \right. \\ \left. + \left(\tan^2 \frac{\theta}{2} + \frac{Q^2}{2q^2} \right) R_{xx} \mp \tan \frac{\theta}{2} \sqrt{\tan^2 \frac{\theta}{2} + \frac{Q^2}{q^2}} R_{xy} \right],$$

where $G_F = 1.1803 \times 10^{-5} \text{ GeV}^{-2}$ is the Fermi constant [16] and the $- (+)$ sign in the last term applies to the $\nu (\bar{\nu})$ reaction. The neutrino initial and final four-momenta are $k^\mu = (\epsilon, \mathbf{k})$ and $k'^\mu = (\epsilon', \mathbf{k}')$, and its energy and momentum transfers are defined as $\omega = \epsilon - \epsilon'$ and $\mathbf{q} = \mathbf{k} - \mathbf{k}'$. The scattering angle and four-momentum transfer are denoted by θ and Q^2 , respectively, with $Q^2 = q^2 - \omega^2 > 0$. The nuclear response functions are schematically given by (explicit expressions are listed in Eqs. (2.5)–(2.9) of Ref. [15])

$$R_{\alpha\beta}(q, \omega) \sim \overline{\sum_i} \sum_f \delta(\omega + m_A - E_f) \langle f | j^\alpha(\mathbf{q}, \omega) | i \rangle \times \langle f | j^\beta(\mathbf{q}, \omega) | i \rangle^*,$$

where $|i\rangle$ and $|f\rangle$ represent the initial ground state and final scattering state of the nucleus of energies m_A and $E_f = \sqrt{q^2 + m_f^2}$; here, m_A and m_f denote, respectively, the rest mass and internal excitation energy (including the masses of the constituent nucleons). The three-momentum transfer \mathbf{q} is taken along the z -axis (i.e., the spin-quantization axis), and $j^\mu(\mathbf{q}, \omega)$ is the NC time component for $\mu = 0$ or space component for $\mu = x, y, z$. Lastly, an average over the initial nuclear spin projections is implied.

The NC is given by

$$j^\mu = -2 \sin^2 \theta_W j_{\gamma,S}^\mu + (1 - 2 \sin^2 \theta_W) j_{\gamma,V}^\mu + j_V^{\mu 5},$$

where θ_W is the Weinberg angle ($\sin^2 \theta_W = 0.2312$ [17]), $j_{\gamma,S}^\mu$ and $j_{\gamma,V}^\mu$ denote, respectively, the isoscalar and isovector components of the electromagnetic current, and $j_V^{\mu 5}$ denotes the isovector component of the axial current. Isoscalar contributions to j^μ associated with strange quarks are ignored, since experiments at Bates [18–20] and JLab [21–23] have found them to be very small.

Explicit expressions for the nuclear electromagnetic current j_γ^μ are reported in Ref. [15] and were used in our recent study of the charge form factor and longitudinal and transverse sum rules of electromagnetic response functions in ^{12}C [14]. In the SNPA they lead to a satisfactory description of a variety of electro- and photo-nuclear observables in systems with $A \leq 12$, ranging from static properties (charge radii, quadrupole moments, and M1 transition widths) to charge and magnetic form factors to low-energy radiative capture cross sections and to inclusive (e, e') scattering in quasielastic kinematics at intermediate energies [14, 24–28].

A realistic model for the axial weak current $j_V^{\mu 5}$ includes one- and two-body terms (see Ref. [15] for a recent overview). The former follow from a non-relativistic expansion of the single-nucleon four-current, in which corrections proportional to $1/m^2$ (m is the nucleon mass) are retained. The time component of the two-body axial current includes the pion-exchange term whose structure and strength are determined by soft-pion theorem and

current algebra arguments [29]. Its space components consist of contributions associated with π - and ρ -meson exchanges, the axial $\rho\pi$ transition mechanism, and a Δ excitation term (treated in the static limit). The values for the π - and ρ -meson coupling constants are taken from the CD-Bonn one-boson-exchange potential [30]. Two different sets of cutoff masses Λ_π and Λ_ρ are used to regularize the r -space representation of these operators [15]: in the first set (Set I) the Λ_π and Λ_ρ values ($\Lambda_\pi = \Lambda_\rho = 1.2 \text{ GeV}$) are in line with those extracted from the effective π -like and ρ -like exchanges implicit in the Argonne v_{18} (AV18) two-nucleon potential [31], while in the second set (Set II) they are taken from the CD-Bonn potential ($\Lambda_\pi = 1.72 \text{ GeV}$ and $\Lambda_\rho = 1.31 \text{ GeV}$). In the N to Δ current, the value for the transition axial coupling constant (g_A^*) is determined by fitting the Gamow-Teller matrix element of tritium β -decay in a calculation [32, 33] based on $^3\text{H}/^3\text{He}$ wave functions corresponding to the AV18 and Urbana IX (UIX) three-nucleon [34] potentials and on the present model for the axial current ($g_A^* = 0.614 g_A$ with Set I and $g_A^* = 0.371 g_A$ with Set II).

The ω -dependence in the current j^μ enters through the dependence on Q^2 of the electroweak form factors of the nucleon and N -to- Δ transition. We fix ω at the quasielastic peak energy, $\omega_{\text{qe}} = \sqrt{q^2 + m^2} - m$, and evaluate these form factors at $Q_{\text{qe}}^2 = q^2 - \omega_{\text{qe}}^2$. Sum rules of NC response functions, defined as

$$S_{\alpha\beta}(q) = C_{\alpha\beta} \int_{\omega_{\text{el}}}^{\infty} d\omega R_{\alpha\beta}(q, \omega),$$

can then be expressed as ground-state expectation values of the type

$$S_{\alpha\beta}(q) = C_{\alpha\beta} \overline{\sum_i} \langle i | j^{\alpha\dagger}(\mathbf{q}) j^\beta(\mathbf{q}) + (1 - \delta_{\alpha\beta}) j^{\beta\dagger}(\mathbf{q}) j^\alpha(\mathbf{q}) | i \rangle$$

$$S_{xy}(q) = C_{xy} \overline{\sum_i} \text{Im} \langle i | j^{x\dagger}(\mathbf{q}) j^y(\mathbf{q}) - j^{y\dagger}(\mathbf{q}) j^x(\mathbf{q}) | i \rangle$$

where $\omega_{\text{el}} = \sqrt{q^2 + m_A^2} - m_A$ is the energy transfer corresponding to elastic scattering, the $C_{\alpha\beta}$'s are convenient normalization factors (see below), $\alpha\beta = 00, zz, 0z$, and xx , and for $\alpha\beta = xx$ the expectation value of $j^{x\dagger} j^x + j^{y\dagger} j^y$ is computed. Note that the sum rules as defined above include the elastic and inelastic contributions; the former are proportional to the square of electroweak form factors of the nucleus. In the large q limit, these nuclear form factors decrease rapidly with q , and the sum rules reduce to the incoherent sum of single-nucleon contributions. The normalization factors $C_{\alpha\beta}$ are chosen such that $S_{\alpha\beta}(q \rightarrow \infty) \simeq 1$, for example

$$C_{xy}^{-1} = -\frac{q}{m} G_A(Q_{\text{qe}}^2) \left[Z \tilde{G}_M^p(Q_{\text{qe}}^2) - N \tilde{G}_M^n(Q_{\text{qe}}^2) \right],$$

where Z (N) is the proton (neutron) number, G_A is the weak axial form factor of the nucleon normalized as $G_A(0) = g_A$ ($g_A = 1.2694$ [17]), and

$\tilde{G}_M^p = (1 - 4\sin^2\theta_W) G_M^p/2 - G_M^n/2$ and $\tilde{G}_M^n = (1 - 4\sin^2\theta_W) G_M^n/2 - G_M^p/2$ are its weak vector form factors (here, G_M^p and G_M^n are the ordinary proton and neutron magnetic form factors, determined from fits to elastic electron scattering data off the proton and deuteron and normalized to the proton and neutron magnetic moments: $G_M^p(0) = \mu_p$ and $G_M^n(0) = \mu_n$).

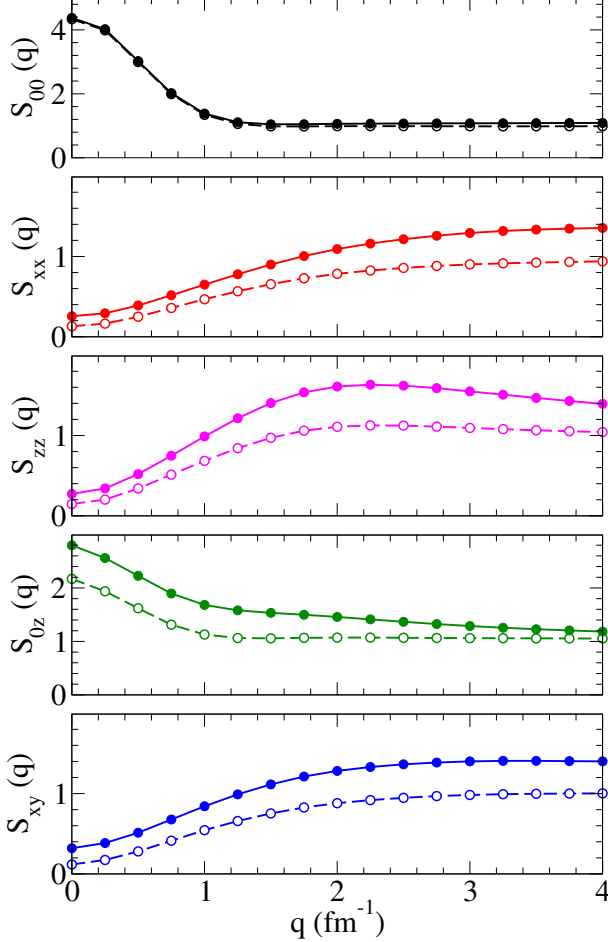


FIG. 1. (Color online) The sum rules $S_{\alpha\beta}$ in ^{12}C , corresponding to the AV18/IL7 Hamiltonian and obtained with one-body only (dashed lines) and one- and two-body (solid lines) terms in the NC.

The ground-state wave function of ^{12}C is obtained from a Green's function Monte Carlo (GFMC) solution of the Schrödinger equation including the Argonne v_{18} (AV18) two-nucleon [31] and Illinois-7 (IL7) three-nucleon [35] potentials. The wave function is evolved in imaginary time via a GFMC propagation starting from a variational wave function that contains both explicit α -clustering and the five possible $J^\pi=0^+$ p-shell states. The predicted ground-state energy, rms charge radius, and charge form factor have been found to be in excellent agreement with experimental data [14].

The sum rules $S_{\alpha\beta}(q)$ in ^{12}C are shown in Fig. 1: results S^{1b} (S^{2b}) corresponding to one-body (one- and two-

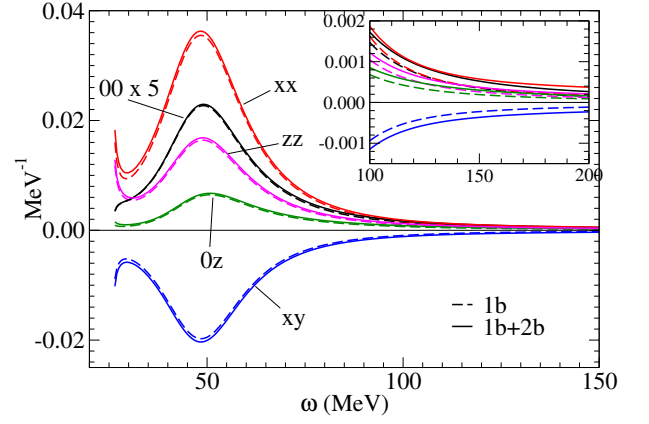


FIG. 2. (Color online) The response functions $R_{\alpha\beta}$ in the deuteron at $q = 300$ MeV/c computed using AV18 and obtained with one-body only (dashed lines) and one- and two-body (solid lines) terms in the NC. The inset shows the tails of $R_{\alpha\beta}$ in the ω -region well beyond the quasi-elastic peak.

body) terms in the NC are indicated by the dashed (solid) lines. The two-body axial currents are those of Set I; we find that Set II leads to very similar results. Note that both $S_{\alpha\beta}^{1b}$ and $S_{\alpha\beta}^{2b}$ are normalized by the (same) factor $C_{\alpha\beta}$, which makes $S_{\alpha\beta}^{1b}(q) \rightarrow 1$ in the large q limit. In the small q limit, $S_{00}^{1b}(q)$ and $S_{0z}^{1b}(q)$ are much larger than $S_{\alpha\beta}^{1b}$ for $\alpha\beta \neq 00, 0z$. In a simple α -cluster picture of ^{12}C , one would expect $S_{\alpha\beta}^{1b}(^{12}\text{C})/C_{\alpha\beta}(^{12}\text{C}) \simeq 3 S_{\alpha\beta}^{1b}(^4\text{He})/C_{\alpha\beta}(^4\text{He})$, as is indeed verified in the actual numerical calculations to within a few %, except for S_{00}^{1b}/C_{00} and S_{0z}^{1b}/C_{0z} at low $q \lesssim 1$ fm $^{-1}$, where these quantities are dominated by the elastic contribution scaling as A^2 . In the α particle, the operators $j^{0\dagger}j^0$ and $(j^{0\dagger}j^z + j^{z\dagger}j^0)$ can connect its dominant S-state components in the left and right wave functions, while the remaining operator combinations cannot and only contribute through S-to-D, D-to-S, and D-to-D transitions—D is the D-state component, which has a probability of $\simeq 15\%$.

Except for $S_{00}^{2b}(q)$, the $S_{\alpha\beta}^{2b}(q)$ sum rules are considerably larger than the $S_{\alpha\beta}^{1b}(q)$, by as much as 30-40%. This enhancement was not seen in calculations of neutrino-deuteron scattering [15]; the deuteron $R_{\alpha\beta}(q, \omega)$ response functions at $q = 300$ MeV/c are displayed in Fig. 2 (note that R_{00} is multiplied by a factor of 5). Two-body current contributions in the deuteron amount to only a few percent at the top of the quasielastic peak of the (largest in magnitude) R_{xx} and R_{xy} , but become increasingly more important in the tail of these response functions, consistent with the notion that this region is dominated by two-nucleon physics [14]. The very weak binding of the deuteron dramatically reduces the impact of two-nucleon currents, which are important only when two nucleons are within 1-2 inverse pion masses.

Correlations in np pairs in nuclei with mass number

$A \geq 3$ are stronger than in the deuteron. The two-nucleon density distributions in deuteron-like ($T=0$ and $S=1$) pairs are proportional to those in the deuteron for separations up to $\simeq 2$ fm, and this proportionality constant, denoted as R_{Ad} in Ref. [36], is larger than $A/2$ (in ^4He and ^{16}O the calculated values of R_{Ad} are 4.7 and 18.8, respectively). Similarly, experiments at BNL [37] and JLab [38] find that exclusive measurements of back-to-back pairs in ^{12}C at relative momenta around 2 fm^{-1} are strongly dominated by np (versus nn or pp) pairs. In this range and in the back-to-back configuration, the relative-momentum distribution of np pairs is an order of magnitude larger than that of pp (or nn) pairs because of tensor correlations induced by pion exchange. The tensor force plays a larger role in np pairs where it can act in relative S-waves, while it acts only in relative P-waves (and higher partial waves) in nn and pp pairs [39, 40]. We find that the enhancement in the weak response due to two-nucleon currents is dominated by $T=0$ pairs, much as was found previously in the case of the electromagnetic transverse response [28]. For S_{xx} and S_{xy} , the enhancement from $T=1$ np pairs becomes appreciable for $q \gtrsim 1 \text{ fm}^{-1}$, while still remaining below $\simeq 15\%$ of that due to $T=0$ pairs. For S_{zz} , contributions from $T=1$ np pairs are larger at $q \simeq 1 \text{ fm}^{-1}$, where they are about 30% of those due to $T=0$ pairs. As for S_{0z} , at small momentum transfer the $T=1$ np -pair contributions are negative and interfere destructively with the $T=0$ ones.

The increase due to two-nucleon currents is quite substantial even down to small momentum transfers. At $q \simeq 1 \text{ fm}^{-1}$, the enhancement is about 50% relative to the one-body values. In general, the additional contributions of the two-nucleon currents (j_{2b}) to the sum rules are given by a combination of interference with one-body currents (j_{1b}), matrix elements of the type $\langle i | j_{1b}^\dagger j_{2b} | i \rangle + \langle i | j_{2b}^\dagger j_{1b} | i \rangle$, and contributions of the type $\langle i | j_{2b}^\dagger j_{2b} | i \rangle$. At low momentum transfers we find the dominant contributions are of the latter $\langle i | j_{2b}^\dagger j_{2b} | i \rangle$ type, where the same pair is contributing in both left and right operators. One would expect the matrix element of any short-ranged two-body operator in $T, S = 0, 1$ np pairs, like the two-body weak currents under consideration here, to scale as R_{Ad} . Enhancements of the response due to two-nucleon currents could be important in astrophysical settings, where the neutrino energies typically range up to 50 MeV. A direct calculation of the ^{12}C response functions is required to determine whether the strength of the response at low q extends to the low energies kinematically accessible to astrophysical neutrinos.

At higher momentum transfers the interference between one- and two-nucleon currents plays a more important role. The larger momentum transfer in the single-nucleon current connects the low-momentum components of the ground-state wave function directly with the high-momentum ones through the two-nucleon current. For

nearly the same Hamiltonian as is used here, there is a 10% probability that the nucleons have momenta greater than 2 fm^{-1} implying that $\approx 30\%$ of the wave function amplitude is in these high-momentum components [41]. The contribution of np pairs remains dominant at high momentum transfers, and matrix elements of the type $\langle i | [j_{1b}(l) + j_{1b}(m)]^\dagger j_{2b}(lm) | i \rangle + \text{c.c.}$ at short distances between nucleons l and m are critical.

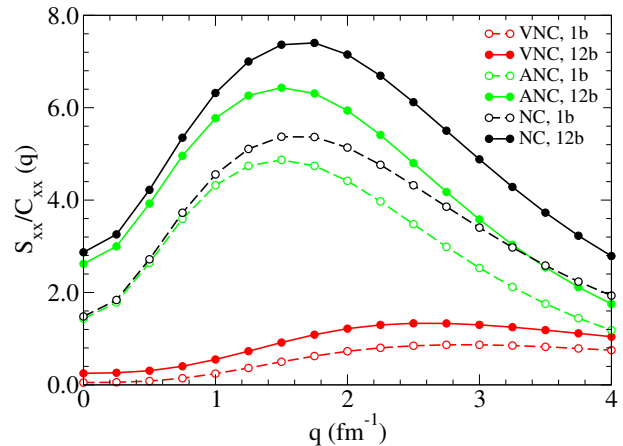


FIG. 3. (Color online) The S_{xx}/C_{xx} sum rules obtained with the NC (curves labeled NC) and either its vector (curves labeled VNC) or axial-vector (curves labeled ANC) parts only. The corresponding one-body (one- and two-body) contributions are indicated by dashed (solid) lines. Note that the normalization factor C_{xx} is not included.

In Fig. 3, we show, separately, for the S_{xx}/C_{xx} sum rule the contributions associated with the vector (VNC) and axial-vector (ANC) parts of the NC. We find that the ANC piece of the S_{xx} sum rule has large two-body contributions (of the order of 30% relative to the one-body). Similar results are found for the $0z$ and zz sum rules; the xy sum rule is nonzero because of interference between the VNC and ANC and vanishes in the limit in which only one or the other is considered. The ANC two-body contributions in the sum rules studied here are much larger than the contributions associated with axial two-body currents in weak charge-changing transitions to specific states at low-momentum transfers, such as β -decays and electron- and muon-capture processes involving nuclei with mass numbers $A=3-7$ [33, 42], where they amount to a few % (but are nevertheless necessary to reproduce the empirical data).

In conclusion, the present study suggests that two-nucleon currents generate a significant enhancement of the single-nucleon neutral weak current response, even at quasi-elastic kinematics. This enhancement is driven by strongly correlated np pairs in nuclei. The presence of these correlated pairs also leads to important interference effects between the amplitudes associated with one- and two-nucleon currents: the single-nucleon current can knock out two particles from a correlated ground state,

and the resulting amplitude interferes with the amplitude induced by the action of the two-body current on this correlated ground state. The present results can be used as constraints for more phenomenological approaches to the nuclear response, and to guide improvements to these models and experimental analyses of quasi-elastic scattering in neutrino experiments.

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